U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
PB-295 007

Flue Gas Desulfurization Pilot Study. Phase I Survey of Major Installations. Appendix 95-F Lime/Gypsum Flue Gas Desulfurization Process

NATO Committee on the Challenges of Modern Society, Brussels (Belgium)

Jan 79

PB 295007

COMMITTEE ON THE CHALLENGES
OF MODERN SOCIETY

Flue Gas Desulfurization Pilot Study Phase I — Survey of Major Installations - Lime/Gypsum Flue Gas Desulfurization Process

Appendix 95-F

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SPRINGFIELD, VA. 22161

NORTH ATLANTIC TREATY ORGANIZATION

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
95-F		PB295007

4. TITLE AND SUBTITLE	5. REPORT DATE
Flue Gas Desulfurization Pilot Study Phase I - Survey of Major Installations - Lime/Gypsum Flue Gas Desulfurization Process	January 1979
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Federal Republic of Germany	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Battelle-Institut e.V., Frankfurt am Main	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
U.S. Environmental Protection Agency Office of Research and Development (RD-681) 401 M Street, S.W. Washington, D.C. 20460	14. SPONSORING AGENCY CODE EPA/600/00

15. SUPPLEMENTARY NOTES This report is one of a series on the status of flue gas desulfurization processes in the NATO Countries and Japan. In this program, the U.S., the Federal Republic of Germany, and Norway each acted as lead countries to gather information and prepared reports on FGD processes.

16. ABSTRACT Lime/gypsum flue gas desulfurization (FGD)-systems are well suited for relatively high populated areas like Japan and Europe. The production of salable gypsum contributes economical advantages.

Good experience exists in the application of commercial units, which have been operating for several years.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Flue gases Lime/Gypsum Flue Gas Desulfurization Alternatives	NATO Federal Republic of Germany	68A 97F

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
RELEASE TO PUBLIC - BEST AVAILABLE COPY.	UNCLASSIFIED	52
	20. SECURITY CLASS (This page) UNCLASSIFIED	22. PRICE PC A04 MF A01

EPA Form 2220-1 (9-73)

NATO-CCMS STUDY

PHASE I

Flue Gas Desulfurization Pilot Study Phase I

Survey of Major Installations -Lime/Gypsum Flue Gas Desulfurization Process

APPENDIX 95-F

Lead Country - Federal Republic of Germany

Prepared by

Dr. N. Haug, Umweltbundesamt, Berlin
G. Oelert, Battelle-Institut e.V., Frankfurt am Main
Dr. G. Weisser, Battelle-Institut e.V., Frankfurt am Main

January 1979

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Summary

Lime/gypsum flue gas desulfurization (FGD)-systems are well suited for relatively high populated areas like Japan and Europe. The production of salable gypsum contributes economical advantages.

Good experience exists in the application of commercial units, which have been operating for several years.

In Japan the lime/gypsum systems reach nearly 100 % availability, around 90 % SO_2 removal efficiency and very low liquid-to-gas ratios. There are no major chemical, mechanical and design problems left, which could affect wide-spread application of lime/gypsum scrubbing.

R+D efforts are similar to those of the lime/sludge processes. They aim at technical and economical optimization and at increasing the knowledge concerning the factors that cause or prevent oxidation of sulfite, thus enhancing or inhibiting scaling.

The advantages and disadvantages of the lime/gypsum FGD system are as follows:

Advantages

(1) The basic process is fairly simple and contains few steps.

(2) Capital and operating costs are relatively low, and lime is fairly abundant in many countries.

(3) SO_2 removal efficiencies are generally high, on the order of 90 percent.

(4) The two-stage treatment of flue gases permits simultaneous removal of SO_2 and particulates.

(5) Successful performance has been demonstrated, particularly in terms of SO_2 removal on coal-fired systems.

(6) The product gypsum is salable, or it makes an excellent landfill.

Disadvantages/Problems

(1) Fly ash and chloride affect product quality.

(2) If not operated attentively lime/gypsum systems have a tendency towards chemical scaling, plugging and erosion. Excess air, pH, fly ash, residence time in the reaction tank and the presence of NO_2 in the flue gas are suspected to be contributing factors.

Except for one plant, the questionnaires distributed for this study were returned with inadequate information, so that the evaluation necessarily is incomplete, especially with respect to cost aspects. The individual questionnaire data of all plants has been compiled in Table 6 (see appendix) in order to provide an overall survey.

1. Background and Introduction

This report is one of a series on the status of flue gas desulfurization processes in the NATO Countries and Japan. In this program, the United States, the Federal Republic of Germany, and Norway each acted as lead countries to gather information and prepared reports on FGD processes.

The history of lime/limestone scrubbing is closely connected with that of water scrubbing. Dissolved alkaline carbonates ($CaCO_3$ and $MgCO_3$) present in natural water mainly acted as absorbents for SO_2. Moreover, in many of the water-scrubbing tests a small amount of lime or limestone was added.

The most thorough study of water scrubbing appears to have been made by the London Power Co. around 1930:

- Based on experience gained with a test unit (4.5 t/h coal), a large once-through water flow gas washing plant was installed at the Battersea Power Station, London. Initially, the water scrubbing was boosted by addition of limestone slurry; later on, only limestone slurry was applied.

- The Battersea process was later installed also at the London Bankside power plant.

- The London Fulham power station FGD plant was planned next, but for environmental protection reasons no more scrubbing effluent should be discharged into the Thames. In order to produce a solid output of the FGD plant the ICI-Howden process was developed.

- The ICI-Howden Process was first applied on a full scale at the Sir John Power Station in Swansea, England. The FGD unit was shut down due to technical problems.

The production of salable gypsum instead of disposable sludge makes the lime/gypsum process advantageous over the lime/sludge process especially in areas where land is scarce for disposal. If land is abundant and gypsum is not desired by the market, gypsum makes a more stable land-fill than sulfite sludge, giving preference to later use of the disposal pond as construction site. Gypsum can be deposited easily because of its non-thixotrope behaviour compared with calcium sulfite.
In Germany two lime/gypsum plants were commissioned by Saarberg-Hölter in 1974. One (30,000 m^3/h) was designed for purification of waste incinerator stack gas, absorbing HCl, HF and SO_2 simultaneously; the other one (surveyed in this study) desulfurizes flue gas from a coal fired power plant.

Most of the lime/gypsum activities were undertaken in Japan. Here, the first lime/gypsum unit (63,000 m^3/h) was started-up in 1964. 21 units are in operation as per the end of 1977.

2. General Process Description

The basic principles are essentially the same for all lime systems. A lime-water slurry is contacted with flue gas containing SO_2. The SO_2 transfers into the slurry and reacts with the lime. The by-products are calcium sulfite hemihydrate or gypsum. Calcium sulfite hemihydrate is generally ponded or dewatered and landfilled. Gypsum is either dewatered and landfilled or sold. Figure 1 depicts the process schematically.

2.1. Process Chemistry

The overall reactions that take place in the absorber are:

Chemical Reactions

Dissolution of lime: $CaO + H_2O \longrightarrow Ca(OH)_2$

Absorption of SO_2: $Ca(OH)_2 + SO_2 \longrightarrow CaSO_3 \cdot 1/2H_2O + 1/2H_2O$

Oxidation with air in the oxidizing tower:

$CaSO_3 \cdot 1/2H_2O + 1/2O_2 \longrightarrow CaSO_4 \cdot 2H_2O$

$HSO_3^- + 1/2O_2$ (in solution) $\longrightarrow SO_4^{--} + H^+$

$CaSO_3 \cdot 1/2H_2O + H^+ \longrightarrow Ca^{++} + HSO_3^- + 1/2H_2O$

$Ca^{++} + SO_4^{--} + 2H_2O \longrightarrow CaSO_4 \cdot 2H_2O$

Control Theory

The pH of the slurry discharged from the absorber is 4 to 4.5. The pH is then adjusted to 3.5 to 4 (addition of H_2SO_4) to promote oxidation in the subsequent step.

Reaction Kinetics

For simulation a reaction model is used in which the dissolution of lime is the rate determining step.

Stoichiometric Requirement: 1.0

In a variation (for example Saarberg-Hölter) of the lime/gypsum process, a buffer substance is added together with $CaCl_2$ to the scrubbing liquid and thus a clear liquid is received:

Chemical Reactions

$Ca(OH)_2$ suspension + $2HCl \longrightarrow CaCl_2 + 2H_2O$

Absorption

$$\begin{cases} CaCl_2 + 2SO_2 + 2H_2O \longrightarrow Ca(HSO_3)_2 + 2HCl \\ Ca(OH)_2 + 2SO_2 \xrightarrow{(+\ acid)} Ca(HSO_3)_2 \end{cases}$$

Oxidation

$$\begin{cases} Ca(HSO_3)_2 + O_2 \longrightarrow CaSO_4 + H_2SO_4 \\ H_2SO_4 + Ca(OH)_2 \longrightarrow CaSO_4 + 2H_2O \end{cases}$$

Absorption $Ca(OH)_2 + SO_2 \longrightarrow CaSO_3 + H_2O$

Neutralization $2HCl + Ca(OH)_2 \longrightarrow CaCl_2 + 2H_2O$

Control Theory

pH 5 - 0.5 at the scrubber outlet due to additives,
pH 8 - 12 at the scrubber inlet ("Absorben 75")."Absorben 75" acts as a buffer reagent in the scrubbing liquid, it also increases the level of desulfurization by raising the amount of calcium ions and prevents deposits without impairing the oxidation of SO_2·L/G ratio can be kept very low: 1.5-2 l/m^3.

When a venturi scrubber is used to remove particulate matter, the particulates thus removed also combine with the sludge. The final gypsum by-product contains 7 to 20 percent free water.

2.2. Description of Equipment Components

2.2.1. Primary Particulate Removal

The primary particulate removal device on coal-fired power plants can be either a venturi scrubber or an electrostatic precipitator (ESP). The primary particulate removal device on an oil-fired boiler is an ESP. An ESP removes particulates from the flue gas before it enters the scrubber. Particulate matter in the by-product gypsum reduces the quality of the gypsum. In some units, an ESP is followed by two SO_2 scrubbers. Most of the

ESP-product is discarded, but some is sold for cement. In most of the systems, fly ash is removed before scrubbing to produce a high-quality gypsum.

2.2.2. Gas Cooler

The gas cooler is used on oil-fired boilers to cool and humidify the gas before it enters the scrubber. Cooling the gas improves the SO_2 removal rate and protects plastic packings and coatings. Humidifying the gas reduces reposits and scaling in the scrubber. When there are two scrubber units, the first scrubber takes the place of the gas cooler. The second scrubber, or absorber, is the primary SO_2 removal unit in the system and is designed to provide intimate contact between the flue gas and the slurry.

2.2.3. SO_2 Absorber

Scrubber design varies among the processes. The scrubber is a spray tower packed with plastic, a venturi, a Turbulent Contact Absorber (TCA) with polyethylene balls, a stainless steel screen type, a perforated plates tower or a Rotopart ® gas scrubber. The reliability of the Mitsubishi-JECCO packed tower and Chemico venturi scrubber has been well demonstrated in Japan. The former has less pressure drop. The TCA scrubber has a high SO_2 removal efficiency but presents the problem of ball wear. The perforated plate scrubber is designed to give extreme turbulence-producing foam layers 15 to 20 inches thick and a high SO_2 removal efficiency is attained during the formation of heavy mist. Also the Rotopart ® scrubber*) developed for the Saarberg-Hölter process has been operated successfully.

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*) see Process Description in the Appendix, Section 7

2.2.4. Demister

A demister is required downstream from the absorber to remove entrained water droplets and thereby decreases downstream equipment corrosion or scaling. This requires additional reheater energy to evaporate the droplets. The droplets are large enough to be removed by a simple change in gas direction. Cyclonic or Z-type vane designs are adequate and can be stacked to provide additional capacity. Spray washers are installed to reduce the scaling and corrosion to which demisters are subject. Stainless steel and fiberglass-reinforced polyester demisters are more resistant to corrosion. Although demisters can be installed in the horizontal or vertical position, the vertical position is much more effective. A horizontal demister allows captured water to drip back into the gas stream and become reentrained.

2.2.5. Reheater

Plume dispersion generally is maintained by heating the stack gas to increase its buoyance. The dispersion makes it possible to meet ambient SO_2 and NO_x standards at ground level and also protects downstream equipment and prevents formation of acid mist. Reheat generally ranges from 100 to 150°C reheater outlet temperature and can be accomplished by one of the following methods: installing a gas or oil burner exhausting directly into the stack, installing steam coils to heat flue gas, injecting steam-coil-heated air into the stack, or injecting flue gas directly from the economizer into the stack. The Japanese prefer the first option. In-line heat exchangers have the lowest initial capital cost, but they are subject to scaling and corrosion and the resultant high maintenance costs.

2.2.6. Slurry Flow

To prepare the slurry, milled lime is added with water. The slurry, which is 3 to 10 percent solids, is mixed with scrubber effluent. This mixture is then injected into the scrubber to remove SO_2. After it passes through the SO_2 absorber, the slurry goes to the venturi scrubber gas cooler or demister spray washer. The slurry is then pumped to the oxidizer for conversion to gypsum.

2.2.7. Gypsum Production

The final step in the system involves oxidation of the calcium sulfite in the slurry to calcium sulfate or gypsum. The Mitsubishi-JECCO-, Babcock-Hitachi, and Chubu-MKK processes use a rotary atomizer invented by JECCO because of its high efficiency and reliability. Different types of oxidizers have been developed for other processes. A low pH (3.5 to 4.), is desirable for oxidation of calcium sulfite slurry to the sulfate. This is attained with a pH controller, by adding less than 1 ton H_2SO_4 per 100 tons of inlet SO_2.

A promising way to moderate the classic scaling problems and to achieve a good gypsum production is represented by the Saarberg-Hölter process, the chemistry of which is described under Section 2.1 (also see "Process Description" in the Appendix, Section 7).

The gypsum by-product is ideal for use in wallboard or cement. Although the crystals formed are not very long, they have considerable thickness, an important factor in the strength of the wallboard made. As long as impurities in the gypsum are kept below critical concentrations, they have no ill effects on the wallboard produced. Chloride content of the gypsum can be as high as 0.5 percent. Fly ash, although imparting a brown

color to the wallboard, sometimes has no adverse effect with concentrations as high as 5 percent. Gypsum used in cement manufacturing can tolerate higher concentrations of both chloride and fly ash without affecting product quality.

The gypsum slurry from the oxidizer is pumped first to a thickener, then to a centrifuge to reduce free water concent. The final gypsum product contains about 10 percent free water.

2.2.8. Wastewater Disposal

The supernatant water from the thickener and the centrifuge is either returned to the system or purged from the system to reduce chloride ion concentrations in the system. Water returned to the system is used to make up new slurry of limestone, spray wash for demisters, or gas precooler spray. Chloride ions accumulate in the scrubber system, especially when coal is the boiler fuel. Chloride attacks both steel and stainless steel.

2.2.9. Schematic Flowsheet

A schematic flowsheet common to most of the processes is represented in Figure 1. Table 1 shows the unit operations applied in each individual plant considered in this study. After leaving the boiler combustion chamber, the flue gas (FG) generally passes through an electrostatic precipitator, after which it enters the FGD plant. The FG is treated in a scrubbing system (mostly 2 stages) followed by a demister. To avoid dew point corrosion and to improve the gas flow, a reheater and a fan complete the treatment before the FG enters the stack.

The scrubbing agent, which consists of a low density lime slurry, is handled by the agent preparation and dosing system.

Through reaction with SO_2 the scrubbing agent forms sulfite slurry, which may be flocculated, dewatered and dumped, or

oxidized in order to produce gypsum. The production of gypsum is particularly advantageous in densely populated areas.

There are different types of wet scrubbers in use at present:

- Fixed throat venturi
- Variable throat venturi
- Turbulent contact absorber (e.g. plastic grid tower)
- Marble bed absorber
- Spray tower
- Perforated plate tower
- "Rotopart" washing tube

In the development of wet SO_2 scrubbers the following main problems arose:

1) Extreme scaling and clogging of the scrubbers often caused by simultaneous scrubbing of flue dust and SO_2.
2) Low absorption efficiency in single-stage operation
3) Clogging and wear of spray nozzles
4) Low demister efficiency
5) Scaling and corroding of reheater
6) Scaling, eroding and corroding of fan
7) Tight pH control necessary

Improvement was achieved by:

ad 1 - Electrostatic precipitation of the flue dust upstream the scrubber. This measure additionally improves the quality of the product gypsum.
ad 2 - Installation of multi-stage scrubbers
ad 3 - Improving of the scrubbing-fluid pH control, nozzle design and choice of nozzle material
ad 4 - Installation of cyclones between scrubber and demister
ad 5 - Direct reheating, e.g. by burners, instead of heat exchangers
ad 6 - Arranging the fan upstream the scrubber
ad 7 - Application of buffer reagents

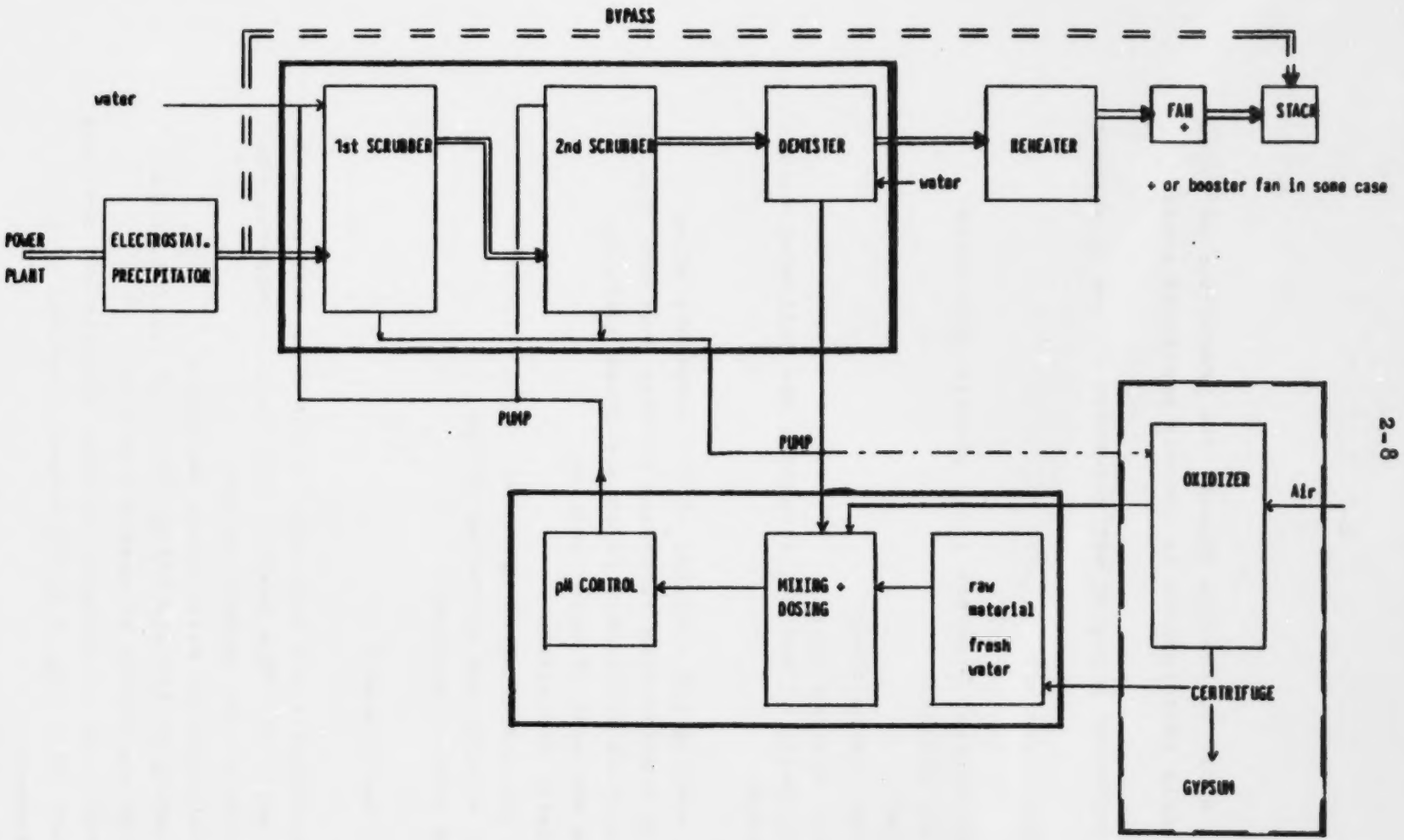

Figure 1: Generalized flow diagram : Lime/gypsum process

	Mitsubishi Jecco Ovese Mita	Saarberg-Hölter Saarbrücken
Electrostatic precipitator	+	+
1st scrubber	spray tower	washing tube
2nd scrubber	grid-packed spray tower	o
Demister	+	(+)
Reheater	+	o
Fan	+	+
Agent preparation + dosing	+	+
Sludge dewatering	o	o
Sludge fixation	o	o
Oxidizer	+	+

+ = applied
o = not applied

Table 1: Unit operations applied in individual lime/gypsum process plants

2.3. Operating Parameters

2.3.1. Chemical Parameters

Lime is added to scrubber systems at a rate of about 1 times the stoichiometric requirement. The pH of various scrubber systems ranges from 8 to 12. Each manufacturer controls the pH to a different level. Systems designed to control pH must rapidly adjust pH back to the control value to avoid reduced efficiency or scaling. This control is especially critical on utility boilers, which frequently change loads. The pH of fresh slurry is controlled in the range of 7.0 to 7.5, whereas the pH of slurry in the oxidizing tower is controlled to 3.5 to 5.0.

2.3.2. Physical Parameters

The primary scrubber in the system can be a particulate scrubber or merely a gas cooler and humidifier. In representative systems in Japan the L/G ratio is about 2 l/m^3, the throat velocity of the scrubbers is 2 to 20 m/s and the pressure drop across the primary scrubber is 3 to 15 mbar.

The second scrubber is the main SO_2 removal device. Its L/G ratio is about 7 l/m^3 the flue gas velocity is 3 to 4 m/s, and the pressure drop across the scrubber is about 15 mbar. In the Saarberg-Hölter process the flue gas scrubber consists of only one stage, the vertically-aligned "Rotopart" washing tube.

Flue gas velocities in vertical demisters average around 6 m/s, whereas the optimum flue gas velocity in horizontal demisters is 2.5 m/s. Higher velocity increases the water removal rate, but it also increases the reentrainment of water before it can leave the demister. Pressure drop across the demister falls in the range of 2.5 mbar.

Flue gas reheat temperature differentials range from 45 to 105°C. This requires an energy expenditure of approx. 1000 J/kg of flue gas/°C of reheat. Pressure drop across the reheater is 1.5 mbar.

3. Current Status and Plans

Lime/gypsum systems are widely used in Japan. 21 units are in operation, additional units are planned and under construction in Japan and FRG.

The Japanese units currently under operation range to capacities of 1,200,000 m^3/h. The quality of the gypsum by-product is similar to that of limestone scrubbers, but limestone is considerably cheaper than lime, so that the trend goes to limestone scrubbing rather than lime scrubbing.

New orders for lime/gypsum - or other FGD systems - are decreasing in Japan for several reasons:

- Fuel desulfurization techniques have been advanced.
- Gypsum supply is becoming excessive, possibly causing a market price drop.
- New technologies for simultaneous SO_2 and NO_x removal are being developed, causing industry to hold back on decisions for new plants.

Table 2 shows the summarized status of lime/gypsum systems. Table 3 presents important characteristics of each surveyed facility. More detailed information can be found in Table 6 in the appendix.

Total Number of Systems in Operation	21
Total Number of Systems Built	21
Total Number of Systems Surveyed	2
Year First Placed in Commercial Service	1964
Number of Utility Systems Using Process	11
Total MW of these Facilities	1800
Number of Industrial Combustion Systems	10
Range of SO_2 Removal Efficiencies (%)	80-92
Range of Fly Ash Removal Efficiencies (%)	99
Range of Availability Factors (%)	85-100

Table 2: Summarized status of lime/gypsum systems

Name of Plant Considered in this Study	Ouasa Mita Chubu Electric Power Co.	Kraftwerk Weiher II, Saarbergwerke AI Saarbrücken
Location	Ouasa bay, Japan	Saarbrücken
Type of Respective Power Plant	oil fired, base load	coal fired, medium load
Size (MW)	750	300
Fuel Characteristics (type/ % S)	heavy oil C / 2.9	coal / 1.0 - 1.4
Heat value (kJ/kg)	43,540	18,000
Flue Gas Treated (m^3/h/ % of total)	2,400,000 / 100	125,000 / 12.5
Year FGD System Started	4/1976	12/1974
Energy Required (MW)	7.5	0.3
SO_2 Removal Efficiency (%)	92	80
Treatment of Other FG Components (% R.)	particulate - ; NO_x - ;	particulate: 100; Cl: 100
Disposition of End Products	gypsum (90 % $CaSO_4$)	gypsum
Average Availability (%/year)	98	96/1976-77

Table 3: Status of surveyed FGD installations

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m^3/h = m^3/h under normal conditions (0 °C, 1 bar)

% R. = % Removal

4. Recent Developments and Solutions to Problem Areas

Scaling, the most significant problem encountered in the lime/gypsum FGD process, results from formation of gypsum crystals on the internal parts of the system. Crystalization of gypsum occurs when the O_2/SO_2 ratio of flue gas is high and oxidation of sulfite to sulfate in the scrubber exceeds 20 percent. This is called saturated-mode operation. Although unsaturated mode operation is being investigated, most systems operate in the saturated mode. To ensure scale-free operation, improvements have been made in the design, fabrication, and operation of the plants. Through pilot plant studies, Mitsubishi Industries determined that scaling can be prevented by shape and arrangement of the grid in the absorber; by adjustment of slurry concentration, pH, and L/G ratio; and by addition of gypsum crystal seed to recirculating slurry; and by thorough mixing of lime in the circulating slurry.

Two additives, magnesium and calcium chloride, have been found to improve performance in lime systems. Magnesium addition helps prevent scaling by acting as an intermediary carrying the SO_2 into solution where it can later react with calcium. The magnesium sulfate solution is separated from the calcium slurry after it is first passed through the scrubber, then mixed with limestone to form magnesium hydroxide and gypsum which is sent back to the scrubber. The gypsum does not grow well and contains about 0.5 percent magnesium sulfate, but it is useful as a retarder of cement setting. The addition of calcium chloride improves the dissolution of lime sixfold or sevenfold. High SO_2 removal can be achieved at L/G's as low as 1 to 2 l/Nm^3. The flue gases cleaned have temperatures as high as 70°C, and reduce the amount of reheating required downstream. The main disadvantages of calcium chloride addition are increased corrosion and low-quality gypsum. The corrosion has been a serious enough problem to cause Kobe Steel, the developer, to use titanium to fabricate the gas cooler.

In order to avoid the negative effects of possible pH values below 7, one process employs a proprietary water soluble additive. It acts as a buffer and reacts chemically in a manner similar to that of the chlorine present in the closed loop.

5. Cost

The questionnaires were returned with inadequate information especially with respect to cost (data from questionnaires are underlined in Table 4); the data in Table 4 are therefore only approximate values, lacking information having been taken from other sources /1, 2, 3, 6/.

Capital costs are partly inflated to the year 1976 using a plant cost index from Chemical Engineering (1957 - 59 = 100; 1972 = 137.2; 1973 = 144.1; 1974 = 165.4; 1975 = 182.4; Jan. 1976 = 187.1.). For evaluating fixed costs per year, a fixed charge factor of 15 % has been assumed for each plant, if no other data have been reported.

Total costs per kWh are subdivided in costs per

- 4000 operating hours p.a.
- 8000 operating hours p.a.

---

1 US $ = 300 Yen
1 US $ = 2.40 DM

	MITSUBISHI JECCO	SAARBERG HÖLTER
	OMASE MITA (750 MW)	WEINER III (654 MW net)
1. Reported capital costs ($) year Costs inflated to 1976 ($)	Total: 28,330,000 (per kW: 37,8) 1976	Total: 50,000,000 (per kW: 76.5) 1977/78
2. Reported annual costs ($) Total fixed costs (fixed chage factor) Total variable costs	6,667,000 (23,5 %) 8,333,000	7,500,000 (15 %) 4,803,000 (4000 h) 8,696,000 (8000 h)
3. Boiler operation hours (capacity factor) Generated MWh, p.a.	6650 (76 %) 4,987,000	4000 / 8000 2,616,000 / 5,232,000
4. Reported cost per kWh (mills) Fixed costs (boiler operation hours) Variable costs	2.22 (4000 h) 1.34 (6650 h) 1.67	2.87 (4000 h) 1.43 (8000 h) 1.84 (4000 h) 1.66 (8000 h)
Total costs per kWh (mills) 4000 h 8000 h	3.9 3.0	4.7 3.1

(Cost data of Saarberg Hölter process are quoted from a tender for the new boiler WEINER III)

Table 4: Cost Data (data reported in the questionnaires are underlined)

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/13/ Saarberg-Hölter Process, Plant Saarbrücken Visit 1.6.1977
(Dr. N. Haug, Dr. G. Weisser, G. Oelert)

/14/ Esche, M.:
Flue Gas Desulfurization and Stack Gas Purification Using the Technology of the Saarberg-Hölter Process.
4th International Congress on the Prevention of Atmospheric Pollution
Tokyo, Japan, May 1977

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7.1. Conversion Factors

multiply		by	to obtain
feet	x	0.30480	m
cub.ft.	x	28.317	l
Btu/lb	x	0.55554	kcal/kg
	x	2.32593	kJ/kg
Btu/h	x	$0.29300 \cdot 10^{-3}$	kW
a.c.f.m. (act. cub.ft. per min.)	x	1.6992	m^3/h
$lb/10^6$ Btu	x	1.80005	mg/kcal
	x	0.42993	mg/kJ
g.p.m.	x	3.78541	ltr/min
(gal. per min.)	x	0.22712	m^3/h
gal/1000 ft^3	x	0.13368	ltr/m^3
ft^3/min	x	1.6992	m^3/h
kcal	x	4.1868	kJ (J = Ws)
kcal	x	$1.163 \cdot 10^{-3}$	kWh
std. cub. ft per min.	x	1.60776	m^3/h (0 °C/1 bar)
grains/ft^3	x	2.288	g/m^3
grains/std. ft^3	x	2.4182	g/m^3 (0 °C/1 bar)
in (inches) water	x	2.54	mbar
grain	x	0.0648	g
ton (short)	x	0.9072	t

1 MW corresponds to 2,800 - 3,500 m^3/h flue gas (depending on excess air)

1 std. cub. ft = 28.317 l (60 °F / 14.7 psia)
(15.5 °C/ 1 bar)
= 26.796 l (0 °C/ 1 bar)
= 0.026796 m^3

ρ_{SO_2} = 2.927 g/l

Table 5: Conversion factors used in this study

7.2. Table 6: Questionnaire Data

		MITSUBISHI JECCO	SAARBERG HÖLTER
		OWASE MITA	WEIHER
1. GENERAL DESCRIPTION			
1.1	Company	Chubu Eletric Power Co.	Saarbergwerke Aktiengesellschaft
1.2	Plant name	Owase Mita	Kraftwerk Weiher
1.3,	Preparers name and mailing address	JumpeiAndo, Chuo University 1-13, Kasuga, Bunkyo-ku, Tokyo,phone:03 813 4171	W. Meyer,KraftwerkWeiher 6600 Saarbrücken, W.-Germany phone: (0681) 4051
1.4	Principal plant products	power	power
	Brief description of area surrounding plant site and factors for choice of FGD system	Located on reclaimed land at Owase bay close to Owase city. Three sides of the city and the power station are surrounded by hills 500 to 1,000 m high.	Located in a hilly rural area about 3 km from a village and 10 km from the city of Saarbrücken. The power plant represents a mine mouth installation.
1.5	Plant location	Owase Mita	Saarbrücken, Quierschied
1.6	STATION CAPACITY		
1.6.1	Total boiler generating capacity (MW)/number of boilers	750/2	300/4
1.6.2	Capacity served by FGD system(MW)	750	37.5
	amount of flue gas treated (m^3/h)	2,400,000	125,000
	% of boiler flue gas treated by FGD system	100	50
	Number of boilers served	2	1

$m^3/h = m^3/h$ (0 °C, 1 bar)

MW = electric power generated

N/A = not available

		MITSUBISHI JECCO	SAARBERG HÖLTER
		OWASE MIE	WEINER
1.7	TYPE OF FGD SYSTEM	lime/gypsum	lime/gypsum
1.8	Number of scrubber trains in parallel	2	1
1.9	FGD system installed on new or existing boiler	exist.	exist.
1.10	STATUS OF FGD SYSTEM operational or under construction, date started	operat. 4/76	operat. 12/74
2.	BOILER DATA		
2.1	Boiler identification number	No. 1	B 2.
2.2	Maximum continous heat input (MW)	1000	198
2.3	Max. cont. net generating capacity (MW)	375	75
2.4	Flue gas flow rate (m^3/h) temperature at induced draft fan	1,200,000 150^0	260,000 150^0
2.5	Boiler manufacturer	Mitsubishi	
2.5.1	Fuel type	heavy oil C	coal
2.5.2	Firing configuration	front firing	slag tap furnace
2.6	Year placed in service	1964	1962
2.7	Type service	base load	medium load
2.8	Stack height (m)	120	50
2.8.1	Flue gas exit velocity (m/s)	27	> 15
2.9	Average boiler operation (h/a)	7500	4500/1976
2.10	Average boiler capacity factor	75.9 %	75 %

	MITSUBISHI JECCO	SAARBERG HÖLTER
	CHASE MITA	WEINER
2.11 COAL COMPOSITION	none	
2.11.1 Lower heating value (kJ/kg) (kcal/kg)		18,000 4,300
2.12.2 Sulfur content (%)		1.0-1.4
2.11.3 Ash content (%)		26
2.11.4 Chloride content (%)		<0.5
2.11.5 Moisture (%)		17
2.12 OIL COMPOSITION		none
2.12.1 Grade / heating value (kJ/kg) (kcal/kg)	43,540 10,400	
2.12.2 Sulfur content (%)	2.9	
2.12.3 Ash content (%)		
2.12.4 Chloride content (%)		
2.13 PARTICULATE REMOVAL EQUIPMENT NOT PART OF FGD SYSTEM		
2.13.1 Type	eletrostatic precipitator	elst. precip.
2.13.2 Manufacturer	Mitsubishi	Rothemühle
2.13.3 Efficiency, % removal	80	>99
2.13.4 Emission rate (ng/m^3)	10	<150

	MITSUBISHI JECCO	SAARBERG HÖLTER
	OWASE MITA	WEIHER
3. EMISSION REGULATIONS		
3.1 ATMOSPHERIC EMISSIONS		
3.1.1 SO_2	126 ppm	
3.1.2 Particulate	10 mg/Nm^3	< 150 mg/Nm^3
3.1.3 NO_x	180 ppm	
3.1.4 Other		
3.1.5 Legal basis	Owase City	Oberbergamt Saarbrücken 19.8.1963
3.2 RESTRICTIONS APPLICABLE TO LIQUID OR SOLID WASTES LEGAL BASIS		
4. FGD SYSTEM INFORMATION		
4.1 Process name	lime/gypsum	lime/gypsum
4.1.1 Supplier or design company	Mitsubishi	Saarberg Hölter
4.1.2 WHY WAS THIS SYSTEM CHOSEN?	Process is simple; plant easy to operate; cheap lime available.	Process developed by operating utility company. Process is simple; no disposal problems; salable product.
4.1.3 PROCESS DESCRIPTION	see text page 7-18	see text page 7-22

	MITSUBISHI JECCO	SAARBERG HÖLTER
	OWASE MITA	WEIHER
4.2 SO_2 SCRUBBING AGENT		
4.2.1 Name	lime	lime
4.2.2 Chemical composition	(75 % CaO)	(or carbide sludge) (DIN 1060) "Absorben 75"
Components / % by weight	CaO / 93-95 Al_2O_3 / 0.5-1.2 MgO / 0.8-1.5	CaO / 95 "Absorben 75" HCl
4.2.3 Stoichiometric requirement	1.0	1.0-1.04
4.2.4 Addition rate (kg/h)	7,760	
4.2.5 Particle size (mm)	< 5 mm	
4.3 REGENERATION AGENT	none	none
4.3.1 Name		
4.3.2 Composition		
4.3.3 Stoichiometric requirement		
4.3.4 Addition rate		
4.3.5 Particle size		
4.4 SALABLE PRODUCT		
4.4.1 Name	gypsum	gypsum
4.4.2 Chemical composition Components / % by weight	$CaSO_4 \cdot H_2O$ / > 90 H_2O / < 10	$CaSO_4 \cdot 2H_2O$ / 95 dust / 5
4.4.3 Amount generated/year (t/a)	90.000	2,000
4.4.4 Sales potential		sales prospects: 100,000 t/a $CaSO_3$: 0.2 - 0.4 % $CaCO_3$: 0.1 - 0.5 % Cl^- : 0.2 - 0.6 %

	MITSUBISHI JECCO	SAARBERG HÖLTER
	OWASE MITA	WEIHER
4.4.5 BY-PRODUCT RECOVERY PROCESS		
Name		
Vendor		
Process description	oxidation + centrifuging	
	Mitsubishi	
4.4a Intermediate product composition		
4.5 BY-PRODUCT NUMBER 2	none	none
4.6 WASTE STREAMS		
4.6.1 Type of waste	water 3 m^3/h	none
% water		
4.6.2 Amount generated in one hour at full load (m^3/h)		
4.6.3 Disposal method	purged after neutralization and clarification	
4.6.4 Disposal site and distance from plant (km)		
4.6.5 Potential effects on environment from sludge disposal		
4.7 SLUDGE FIXATION PROCESS	none	none

	MITSUBISHI JECCO	SAARBERG HÖLTER
4.8 FGD EQUIPMENT DATA	OWASE MITA	WEINER
4.8.1 FIRST SCRUBBER		
4.8.1.1 Type	spray tower	"Rotapart®" washing tube
4.8.1.2 Liquid(solid)/gas ratio(l/m^3)	2.0	1.0-2.5
4.8.1.3 Gas velocity through absorber or scrubber (m/s)	2.5	< 20
4.8.1.4 Absorbent(adsorbent) flow (m^3/h)		
4.8.1.5 Gas flow entering scrubber (m^3/h)	1,200,000 x 2	125,000
4.8.1.6 Gas temperature (°C)	150	150
4.8.1.7 Gas composition		
SO_2 in → out (ppm)	1,600 →	683 → 137
% removal		> 80
Particulate in → out(mg/m^3)	10 →	150 → 0
% removal		100
NO_x in → out (ppm)	180 →	
CO_2 in → out (ppm)		10-11
Other in → out		Cl: → 0/100 %
4.8.1.8 Material of construction		St 37
4.8.1.9 Type of lining	rubber	protective coating
4.8.1.10 Adsorbent and sand losses		
4.8.1.11 Number of stages	1	1
4.8.1.12 Packing type and composition		none

	MITSUBISHI JECCO	SAARBERG HÖLTER
	OWASE MITA	WEINER
4.8.2 SECOND SCRUBBER		
4.8.2.1 Type	grid packed spray tower	none
4.8.2.2 Liquid (solid)/gas ratio (l/m^3)	7	
4.8.2.3 Gas velocity through absorber or scrubber (m/s)	3.4	
4.8.2.4 Absorbent(adsorbent) flow (m^3/h)	1,272,000	
4.8.2.5 Gas flow entering scrubber (m^3/h)	1,272,000	
4.8.2.6 Gas temperature (^oC)	55^o	
4.8.2.7 Gas composition		
SO_2 in → out (ppm)	→ 120	inapplicable
% SO_2 removal	92	
Particulate in → out (mg/m^3)	→ 10	
% removal	0	
NO_x in → out (ppm)	→ 180	
% NO_x removal	0	
CO_2		
Other		
4.8.2.8 Material of construction		inapplicable
4.8.2.9 Type of lining	resin	
4.8.2.10 Number of stages	2	
4.8.2.11 Packing type and composition	plastic grid	

	MITSUBISHI JECCO	SAARBERG HÖLTER
	OWASE MITA	WEIHER
4.8.3 CLEAR WATER TRAY		
4.8.3.1 Type	N/A	none
4.8.3.2 L/G ratio		
4.8.3.3 Source of water		
4.8.4 DEMISTER		
4.8.4.1 Type	Chevron + Eurofora	none
4.8.4.2 Number of passes (stages)	4	
4.8.4.3 Material of construction	PVC	
4.8.4.4 Method of cleaning	fresh water spray	
4.8.4.5 Flow rate during cleanings (m^3/h)	2-16	
4.8.4.6 Frequency and duration of routine cleaning	50 s	
4.8.5 REHEATER		
4.8.5.1 Type	after burner	none
4.8.5.2 Heat load (kW)	9490	
4.8.5.3 Heat transfer surface area (m^2)		
4.8.5.4 Temperature of gas in (^oC)	55	
out (^oC)	100-150	
4.8.5.5 Reheater materials of construction	retractory	

		MITSUBISHI JECCO	SAARBERG HÖLTER
		OHASE MITA	WEIHER
4.8.6	SCUBBER TRAIN PRESSURE DROP DATA		
4.8.6.1	First scrubber (mbar)	3.0	15.0
4.8.6.2	Second rubber (mbar)	15.0	
4.8.6.3	Clear water tray (mbar)		
4.8.6.4	Demister (mbar)	2.5	
4.8.6.5	Reheater (mbar)	1.5	
4.8.6.6	Ductwork (mbar)	15.5	2.0
4.8.6.7	Total FGD system (mbar)	37.5	17.0
5.8.6.8	I.D. fan ΔP (mbar)	37.5	> 17.0
4.9	SYSTEM MAKE-UP WATER ADDED (m^3/h)	98.0	5.0
4.9.1	Water added per mole of SO_2 removed (m^3/kg mol)	1.42	1.44-1.8
4.9.2	Source of make-up water		drinking water quality
4.9.3	Where is water added	cooling tower, demister, centrifuge	as convenient
4.10	BYPASS SYSTEM		
4.10.1	Can flue gas be pypassed?	yes	yes
4.10.2	Height of gas discharge when bypassed (m)		170
4.11	SLURRY DATA		
	pH/% solids by weight		
4.11.1	Fresh slurry to scrubber	12.0 / 5	N/A
4.11.2	Recirculating slurry	6.5-7 /10	
4.11.3	Waste slurry		

	MITSUBISHI JECCO	SAARBERG HÖLTER
4.12 SPENT SLURRY SYSTEM	ONASE MITA	WEIHER
4.12.1 Clarifiers	N/A	
4.12.1.1 Number		
4.12.1.2 Diameter (m)		
4.12.2 Solid separation		
4.12.2.1 Type		vacuum filter
4.12.2.2 Cloth area (m^2)		3.2
4.12.2.3 Capacity (wet cake) (t/h)		1
4.13 SPACE REQUIRED, EXCLUSIVE OF SLUDGE DISPOSAL AREA (m^2)	18,000	none
4.14 PERSONNEL (man-hours/year)		
4.14.1 Operating		
4.14.1.1 Specialists	} 17,000	8,040
4.14.1.2 Unskilled		8,040
4.14.2 Maintenance and repair	14,000	5,400
4.15 ENVIRONMENTAL LOAD		
4.15.1 Waste water treatment process		
4.15.2 Concentrations	SS < 10 ppm; COD < 20 ppm	
4.15.3 Appearance of flue gas discharge - any mist problems?	none	none

	MITSUBISHI JECCO	SAARBERG HÖLTER
	OWASC MITA	WEIHER
4.16 FGD SYSTEM OPERATION		
4.16.1 % of boiler load FGD can operate	30-100	20-110
4.16.2 Lag time	immediately	simultaneously
5. ACTUAL COSTS FOR TOTAL FGD INSTALLATION (year)	300 yen = 1 $	
5.1 CAPITAL COSTS ($)		
5.1.1 Scrubber	N/A	N/A
5.1.2 Absorbent/regeneration system		
5.1.3 Sludge disposal system		
5.1.4 Site improvements		
5.1.5 Land, roads, tracks, substation		
5.1.6 Engineering costs		
5.1.7 Contractor's fee		
5.1.8 Interest during construction		
Construction period (months)		
5.1.9 License fees		
5.1.10 Other		
5.1.11 Total ($)	28,350,000	
($/kW)	37.77	

	MITSUBISHI JECCO	SAARBERG HÖLTER
	OWASE MITA	WEIHER
5.2 ANNUAL COSTS ($)		
5.2.1 Interest		N/A
5.2.2 Depreciation		
5.2.3 Insurance and taxes		
5.2.4 Total fixed costs	6,670,000	
5.2.5 Labor and overhead Average man hour cost cost/year	incl. maintenance	
5.2.6 Raw material breakdown Unit cost Annual cost		
5.2.7 Utilities, unit cost, annual costs		
Electricity Water Steam Fuel		
5.2.8 Maintenance cost per year		
5.2.9 Other costs, list		
5.2.10 Total variable cost per year	8,333,000	
5.2.11 Total annual cost	15,000,000	
5.3 WASTE DISPOSAL COST ($)	nil	nil
Unit cost		
Annual cost		
5.4 BY-PRODUCT CREDIT ($)		
5.4.1 By-product 1	N/A	N/A
5.4.2 By-product 2		

	MITSUBISHI JECCO	SAARBERG HÖLTER
	OMASE META	WEINER
5.5 NET ANNUAL COST		
5.5.1 Cost per kWh for last year (mills)	N/A	N/A
5.5.2 Cost per kWh at maximum continous rating (mills)		
5.5.3 Cost per kWh without FGD		
6. ENERGY REQUIREMENTS		
Pumps (kW)		150
Fan (kW)		150
Reheat (kW)		
Reductant chemicals (kW)		
Other (kW)		
Total (kW)	7,500	300
Per Mg of SO_2 removed(kWh/t SO_2)		

	MITSUBISHI JECCO	SAARBERG HÖLTER
	OWASE MITA	WEINER
7. PERFORMANCE HISTORY; OPERATING PROBLEMS AND SOLUTIONS		
7.1 Scrubber system	Minor scaling in scrubber. Cleaning one in 6 months.	(Process was developed by operating utility company Saarbergwerke.)
7.2 Demister	Slight scaling of demister. Cleaning once in 3 months.	
7.3. Reheater		
7.4 Fan		Erosion
7.5 Sludge system		
7.6 Regeneration system		
7.7 By-product system		
7.8 Other		
7.9 Availability	98 %	96 % (11/76 - 6/77)

7.3. Process Description /12/

7.3.1. Mitsubishi Jecco Process

Flue Gas Cooling

The flue gas is prequenched in the flue gas cooler①, approximately to the adiabatic-saturation temperature by the evaporation of raw water. The water is sprayed into the cooler through a network of internal spray headers and nozzles②. Since the cooler collects a portion of the fly ash remaining in the flue gas, a constant purge stream is taken from the cooler circulating pump discharge③ and transferred to the water treatment system. The prequenched flue gas is demisted by the mist eliminators located at the top.④

Absorbing

After the flue gas has been prequenched and the mist eliminated it enters the absorber⑤, two plastic-grid packed absorber in series are housed in one tower. The lime or limestone slurry is sprayed downward into the absorber through spray nozzles⑥ located at the top. The slurry is drained into the circulation tank⑦ at the bottom, and repumped to the spray nozzles. The pH of the slurry at the circulation pump discharge is controlled by adding fresh lime or limestone slurry to the circulation tank. Through thousands of hours of operating experience,MHI has proven that a very effective method for minimizing scale formation in the absorber is to recirculate a portion of the gypsum slurry from the oxidation tower back to the circulation tank. The addition of seed gypsum provides a sacrificial surface for crystal precipitation, greatly reducing and controlling deposition on absorber surfaces.

Mist Elimination and Reheating

As the flue gas passes through the packed bed, droplets of slurry are entrained. These droplets are removed before the gas is reheated and vented. Chevron blade type mist eliminators[8] are used, and raw water is used for intermittent washing of its surfaces.

The cleaned, demisted flue gas is reheated[9] before it is vented through the stack. The reheater shown here is a direct oil-fired gas heater: however, other methods such as blending of steam heated air can be used if practical for the specific station or plant.

Oxidizing and Gypsum Filtering

The purge stream from the absorber is pumped to the oxidation tower[10], where calcium sulfite and unreacted calcium carbonate in the slurry are converted to calcium sulfate by air oxidation or reaction with sulfuric acid.

A rotary atomizer, an air atomizer of unique design, which generates fine air bubbles at an operating pressure of about 7 bar is used for oxidation. A small amount of sulfuric acid is fed to the tower for conversion of carbonate to sulfate and to promote the oxidation of sulfite to sulfate.

A portion of the purge stream from the oxidation tower is recycled back to the absorber as seed gypsum slurry, and the rest of the slurry is fed to centrifuges for dehydration[11]. The purity of the byproduct gypsum is 98 weight% and contains only 5 to 10 % free water. The gypsum is now ready for shipment as no other treatment is necessary.

The recycle water from the centrifuges is clarified in the thickener.[12] The thickener underflow is fed back to the absorber. A portion of the thickener overflow is transferred to the water treatment system to maintain the concentration of chloride and

other impurities in the recycle streams at a safe level. The rest of the thickener overflow is fed back to the absorbent preparation section of the process.

Absorbent Preparation

Lime is stored in either large silos or a storage building until ready to be used. It is then transferred to a smaller silo equipped with a gravimetric feed conveyor which meters a fixed amount into the lime slurry tank. Recycle water from the gypsum recovery section is mixed with the lime to prepare a constant weight percent slurry to be used as absorbent makeup. Live steam is injected into the lime slurry tank to promote conversion of the lime to calcium hydroxide.

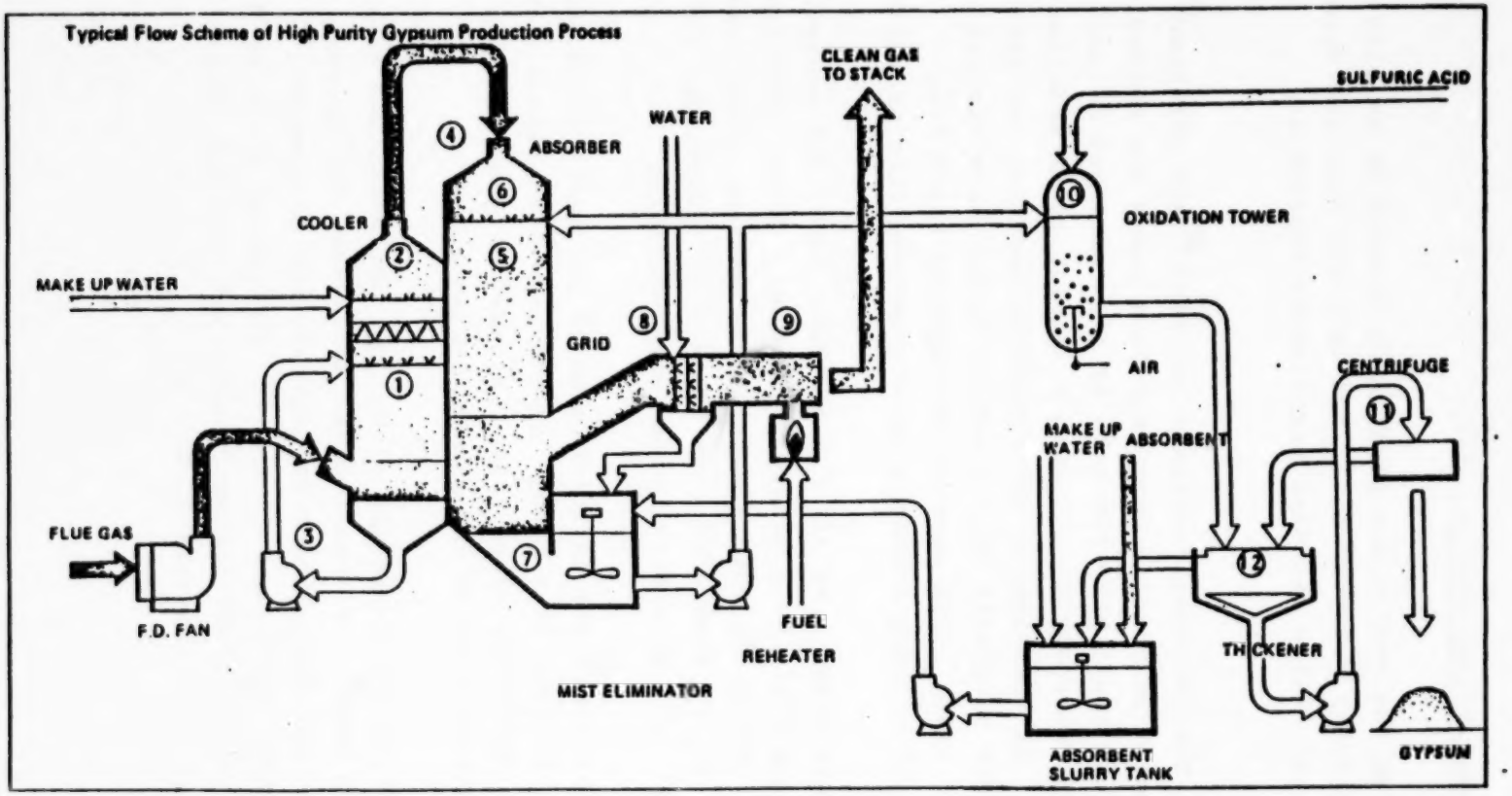

Fig.2 Flow diagram of the MITSUBISHI JECCO Process /12/

7.3.2. Saarberg-Hölter Process /14/

Flue gases from the boiler are preferably treated by an electrostatic precipitator ① before being fed into the flue gas desulfurization plant with a residual particulate content of 150 mg/Nm^3.

On entry into the vertically-aligned ROTOPART ® gas scrubber ② which is arranged in modular form, the flue gases are cooled down in a single stage with the help of jets arranged in one plane and simultaneously washed with a special clear alkaline washing fluid. In addition to the injection nozzles, the circular wash areas - usually some 6 meters long - have special water shedding rings which prevent the washing fluid from running down the washing channels as an inactive film of water.

The desulfurized gases from all the scrubber tubes are separated from the washing fluid by a single rotational partial separator ③ (ROTOPART) and dried. In this separator the washing fluid loaded with dust and SO_2 is separated from the gas by centrifugal force and flushed out through special water scraper rings.

In the oxidation tank ④ air is introduced to produce a substance which consists of over 95 % $CaSO_4$ (gypsum) and less than 0.5 % $CaSO_3$. At the same time, slaked lime is added to compensate for the loss of calcium ions in the gypsum formation.

The gypsum/washing fluid mixture flows from the oxidation tank into a settling tank ⑤, a double-shell clarifier. The gypsum crystals which have been formed precipitate and are purped from the bottom of the tank with a water content of 60 to 80 % into a vacuum filter ⑥. The filter reduces the residual moisture in the gypsum to approximately 20 %.

The damp gypsum drops into a container before being passed on to the gypsum industry for further processing.

Tests have shown that the free water content can be reduced even to below 10 % by using a centrifuge.

The water removed by the vacuum filter is fed back into the settling tank ⑤. At the top of this tank, the clear washing solution (no suspension!) is extracted and re-injected into the scrubber. Thus, the loop of washing fluid is closed.

A control panel accommodates all control, measuring and regulating instruments for the fully-automatic flue gas desulfurization plant. The plant is also set in operation and stopped from this control room. Both procedures take about two to three minutes.

For larger flue gas desulfurization plants this ROTOPART separator also consists of one single unit within which the individual scrubber tubes are arranged in modular form one after another in a row like coke furnace chambers in a coking plant.

The entire washing system is made of standard carbon steel, coated with a simple protective paint. Those parts of the plant which come into contact with the desulfurized flue gas need a protective plastic coating as sub-dewpoint temperatures are unavoidable. It is expedient to provide a rubber lining for the I.D. fan.

Special demisting units to remove the most minute particles of moisture have turned out to be superfluous as the flue gases can be completely dried by the ROTOPART.

The washing fluid separated from the purified gas in the ROTOPART is collected and fed into an oxidation tank.④

It is not necessary to recycle the washing fluid within the scrubber unit itself. This has the advantage over conventional lime processes that neither the residual particulates nor the solid and soluble harmful substances are enriched, which would require a technically extremely complex control system for the washing fluid in the gas scrubber.

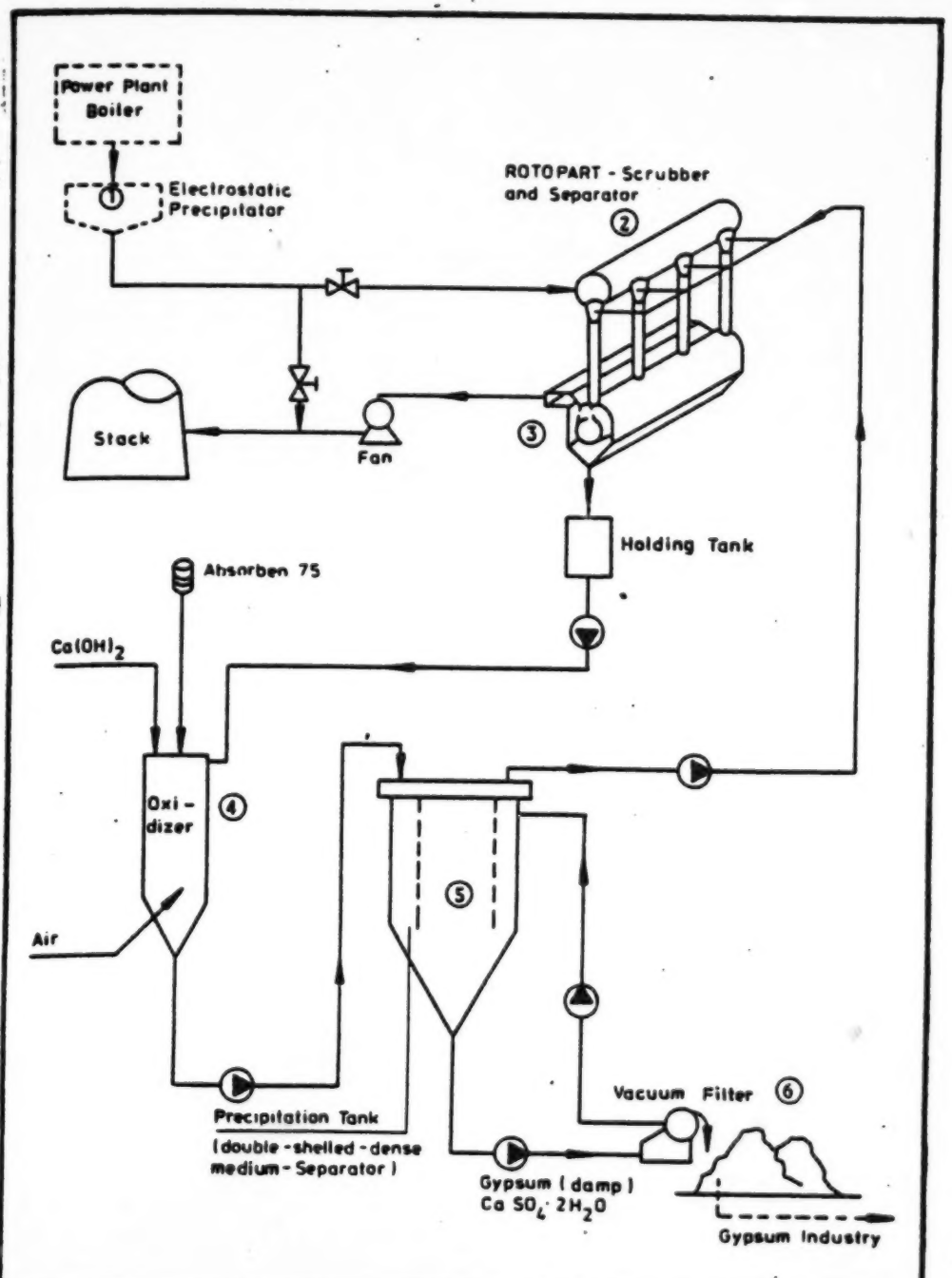

Fig. 3 S-H-Process	Flowsheet of the Flue Gas Desulfurization Plant for a Flue Gas Volume of 125 000 m^3_N/h (80,000 scfm)	Saarberg-Hölter Umwelttechnik GmbH /14/